The Electrode-less Z-Pinch as a metology source in the 20-50 nm range.

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Outline

- Why these wavelengths?
- Theoretical approach
  - How? Brief review of EQ-10
  - Possible gasses
  - Energy balance
- Reality
  - Diagnostics
  - Results
  - Interpretation
- Conclusions

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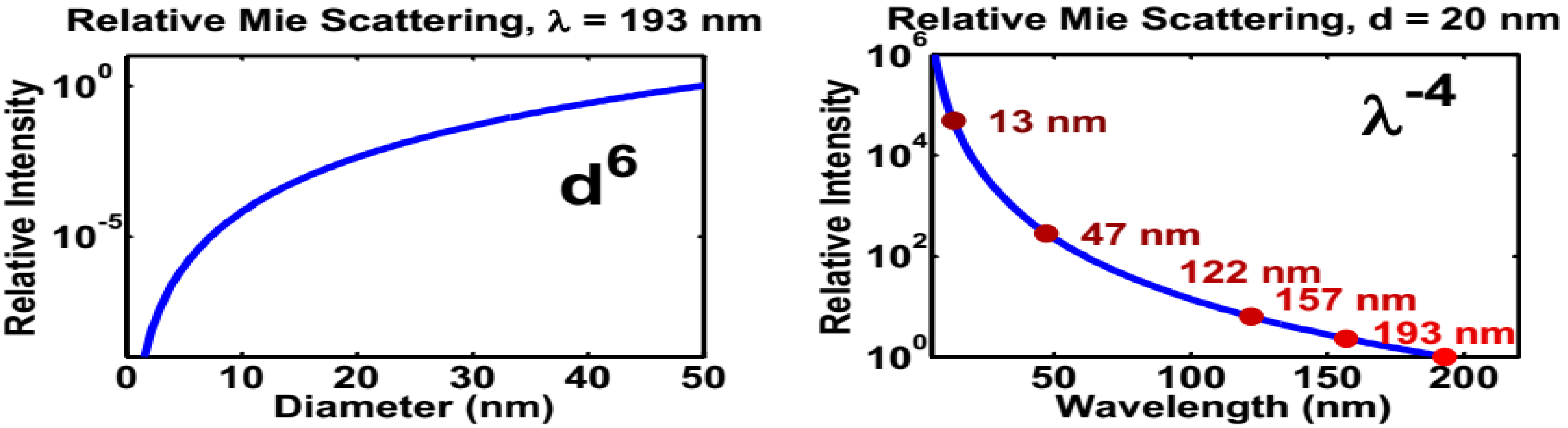
Why does anybody care about 20-50 nm light?

- Most patterned wafer inspection systems rely on broad-band light (down to ~ 200 nm) or lasers (ArF, 193 nm) to detect defects.
- As critical dimensions have been shrinking, so has the size of a so-called “killer defect” that must be detected. Defects are sub-wavelength, so can’t be effectively imaged.
- While the detailed interaction of the illuminating light with the defect is arbitrarily complicated, one can consider Mie scattering as a simpler, perhaps relevant model ….

Mie scattering amplitude from a particle ~d^6/λ^4 (d particle size, λ wavelength)



Trends in relative scattered intensity of a sphere in free space as functions of diameter, *d*, and wavelength, *λ*.

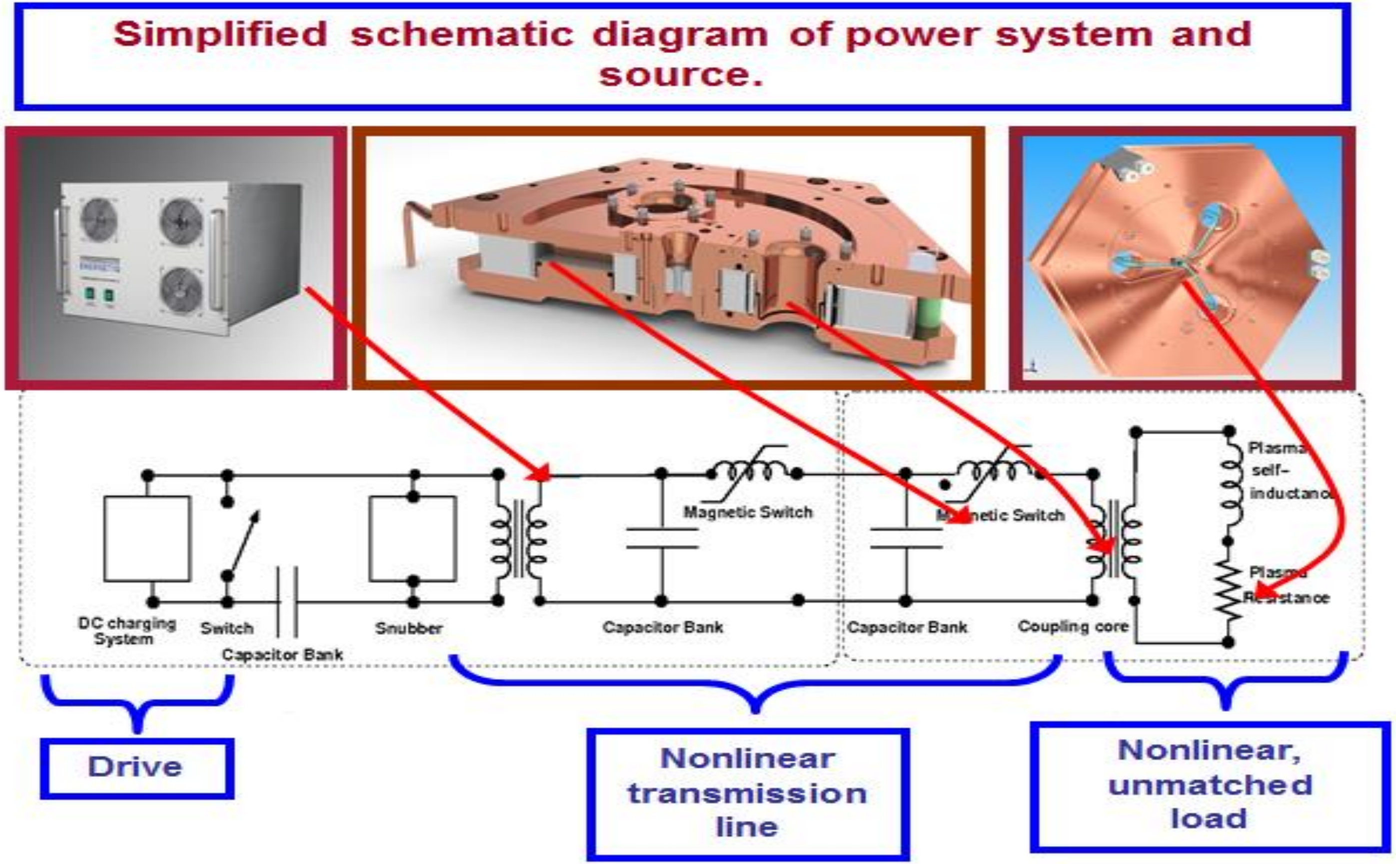
About 200X more signal at 47 compared to 193 nm

Barnes, Bryan M., et al. "Assessing the wavelength extensibility of optical patterned defect inspection." *SPIE Advanced Lithography 2017: Metrology, Inspection, and Process Control for Microlithography XXXI*. Vol. 10145. 2017.

How do we make the light?

If all you have is a hammer, everything looks like a nail..

If all you have is a Z-pinch, everything looks like a plasma…



Horne, Stephen F., et al. "Development of a High Pulse Rate EUV Source." *Proceedings of SPIE, the International Society for Optical Engineering*. Society of Photo-Optical Instrumentation Engineers, 2009.

Available from www.energetiq.com

Z-pinch in Xenon - a baseline

- Source produces ~ 20W inband (13.5 nm +/- 1%, 2 pi) in Xenon; ~ 60 W at 11 nm
- Te ~ 20 eV
- Plasma starts out at ~ 100 mT gas, 1 cm long by 3 mm radius cylinder; N ~ 3.5e21/M^3; about 10^{15} atoms in the pinch
- Compresses to ~ 0.2 mm radius; requires ~ 1.4 J/pulse; density increase of ~200
- Energy/radiating particle - ~ 1.4J/10^{15} particles /q ~= 9keV/particle
- Energy required to ionize Xenon from neutral all the way to Xe+10 ~ 800 eV
- Ratio – takes about 10X theoretical minimum to produce the radiating particle.

If we want to make 20-50 nm, we need to choose a working gas

- NIST spectral database used; http://physics.nist.gov/PhysRefData/ASD/lines_form.html
- Search for lines with high relative intensity. Neon, Argon look like candidates… NIST tables more complete for Neon…
- Ideal radiative state will have an ionization barrier – works for 2.88 nm in Nitrogen for Water Window microscopy (Helium-like nitrogen) but nature isn't always so kind…
- Neon has many lines in this range – from 20 nm to 50 nm.
- Ne +3 (IV) looks promising…

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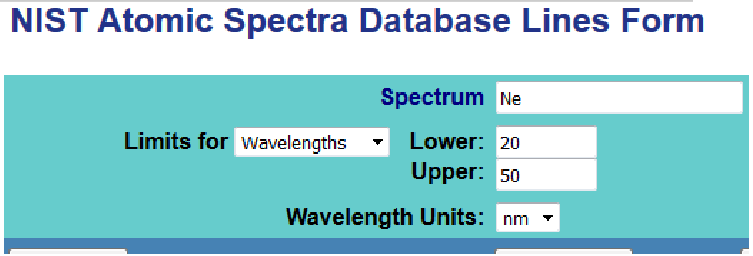
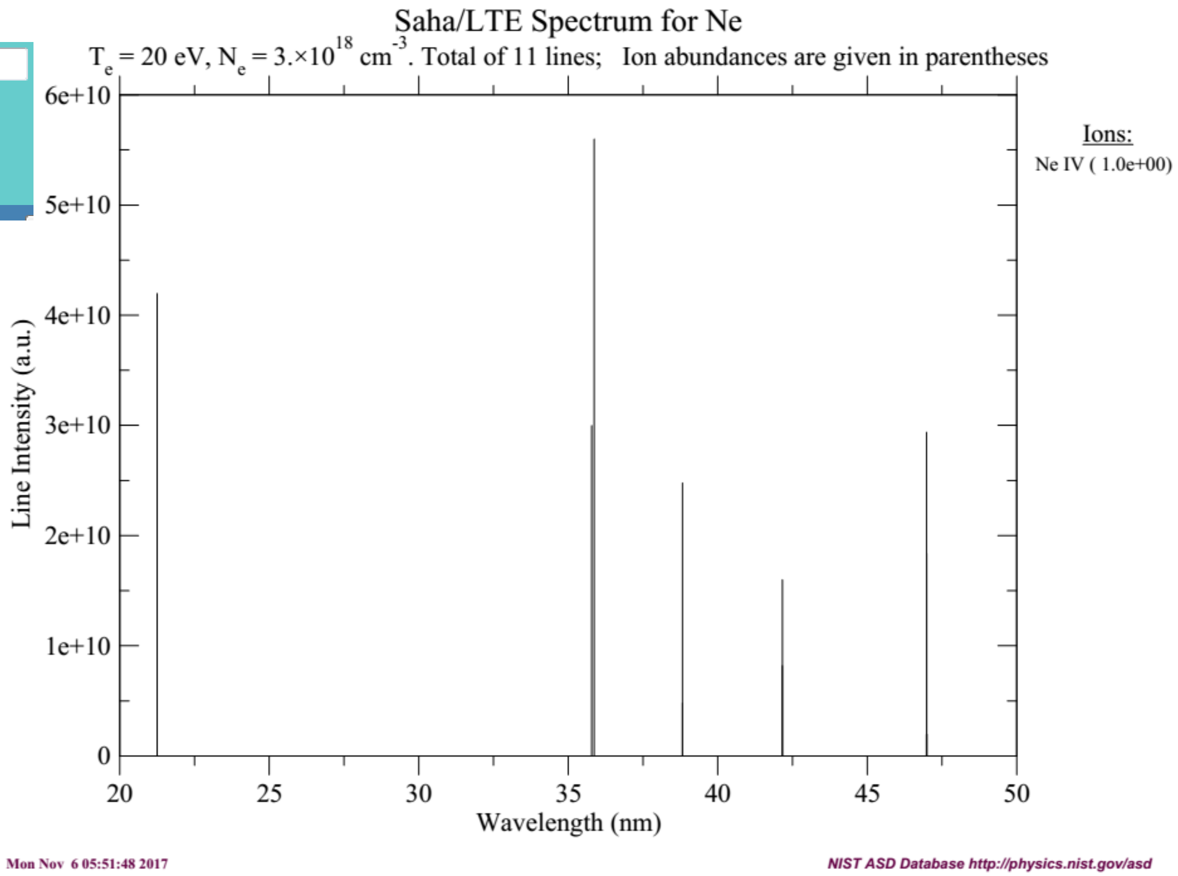
NIST will estimate a spectrum – but beware…



This looks ideal – but there's a problem.

We asked for ALL the ionization states – but specified only strong lines. NIST filters first on the line strength, then includes only those transitions in the calculation. So concludes only Ne +3 in the plasma. Correct, but only if we can get exquisite control of the charge states!



Try to compare Xe +10 and Ne +3…

Plasma	Xe +10 (XI)	Ne +3 (IV)
plasma length	0.01	0.01
radius	0.003	0.003
volume	2.827E-07	2.82743E-07
pressure, mt	100	600
total particles	1.00E+15	6.00E+15
Initial density	3.5E+21	2.1E+22
Pinched radius	2.00E-04	2.00E-04
Volumetric compression	225	225
pinched density	8.0E+23	4.8E+24
N, cgs	8.0E+17	4.8E+18
Joules/pulse	1.4	1.4
Joules/pulse/particle	1.40E-15	2.33E-16
ev/pulse/particle	8753.7	1459.0
Sum of ionizations	806	126
Ratio	10.86	11.58

Boost the pressure…

Estimate how many eV required to produce the charge state we want by summing ionization energies – compare to Z-pinch eV/particle

To get a similar ratio…

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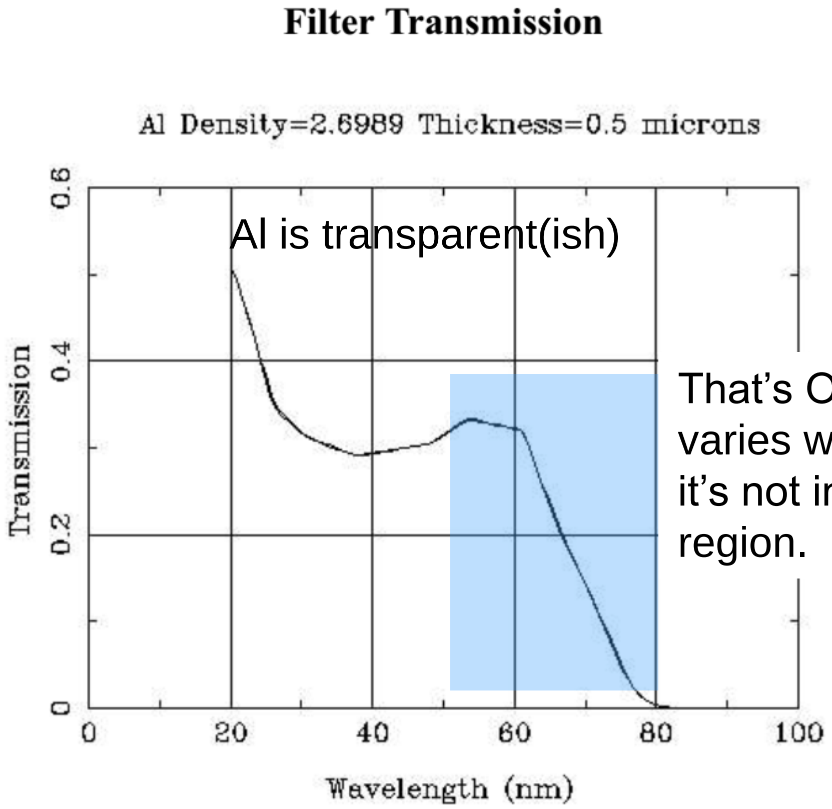
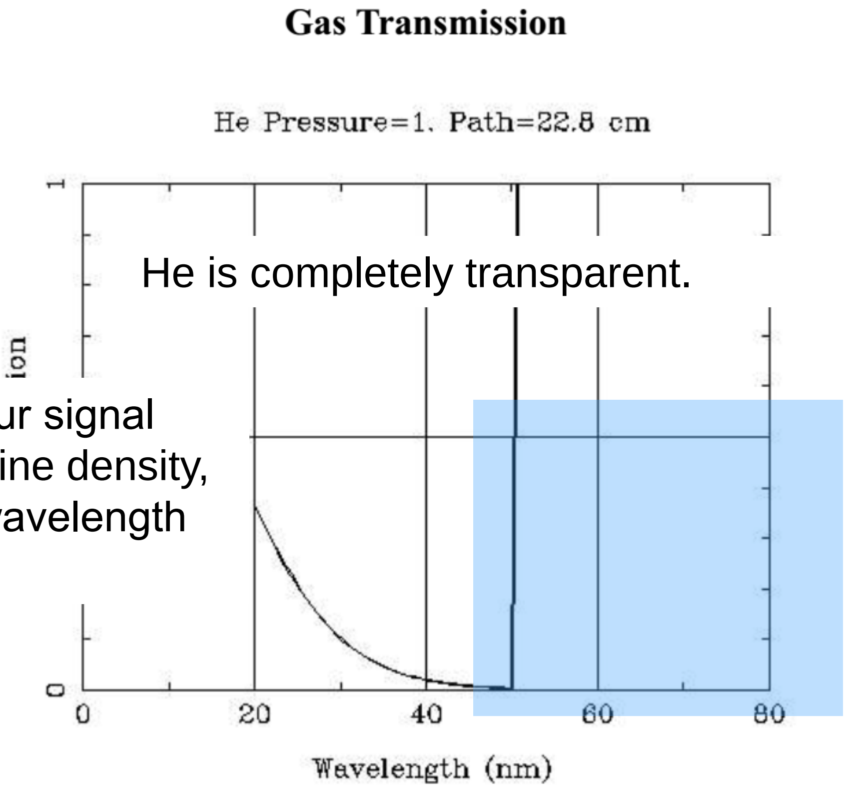
Do the experiment… Run the source in Neon, and measure – how? Need a diagnostic...

- Ideal diagnostic – absolutely calibrated, VUV spectrometer.
  Don't have one.
- Simple diagnostic – metal X-ray filters on VAT valves, gas filter, and an X-ray diode. Look at dependence of detected x-ray power as gas filter line density is varied. Compare to Berkeley CXRO data.
- Aluminum has a nice window in this range. Two 500 nm thick filters allows in situ transmission calibration.
- Helium has a convenient cutoff well matched to the Aluminum windows.
- Note – technique will be biased to detecting higher energy lines
  - Lower energy lines will decrease with pressure more rapidly, leaving the higher energies to be detected…

A subtle point.. what about 50-80 nm?



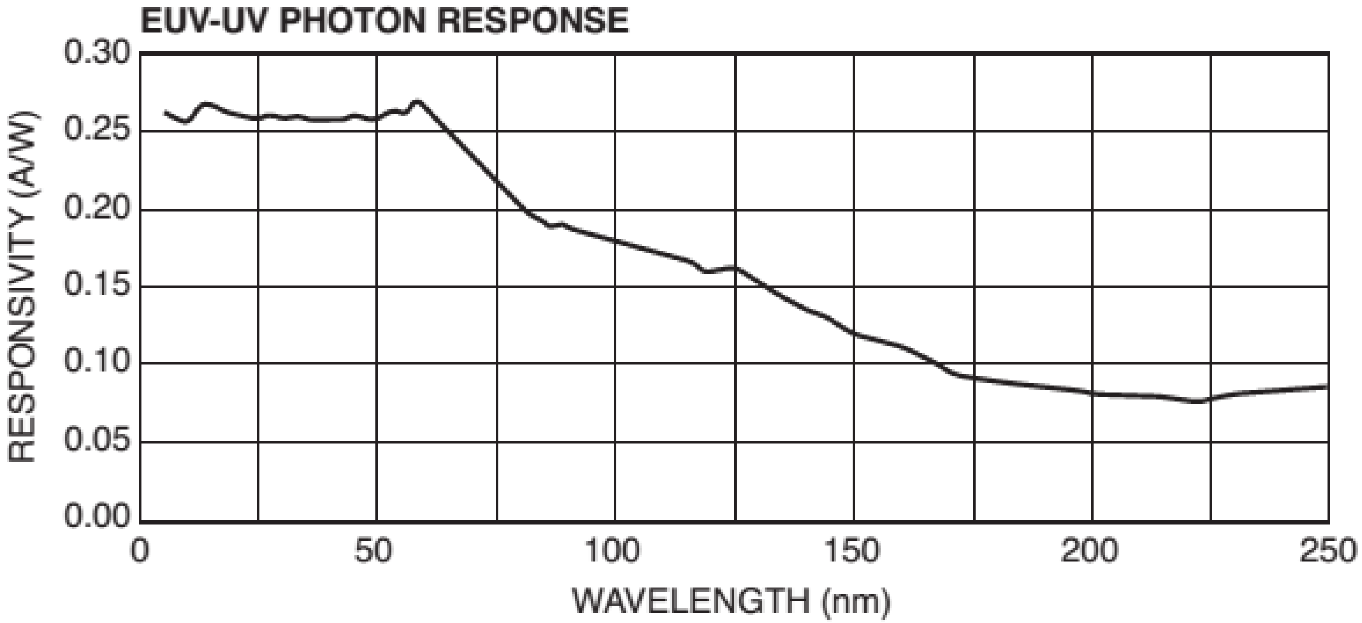
Al is transparent(ish)



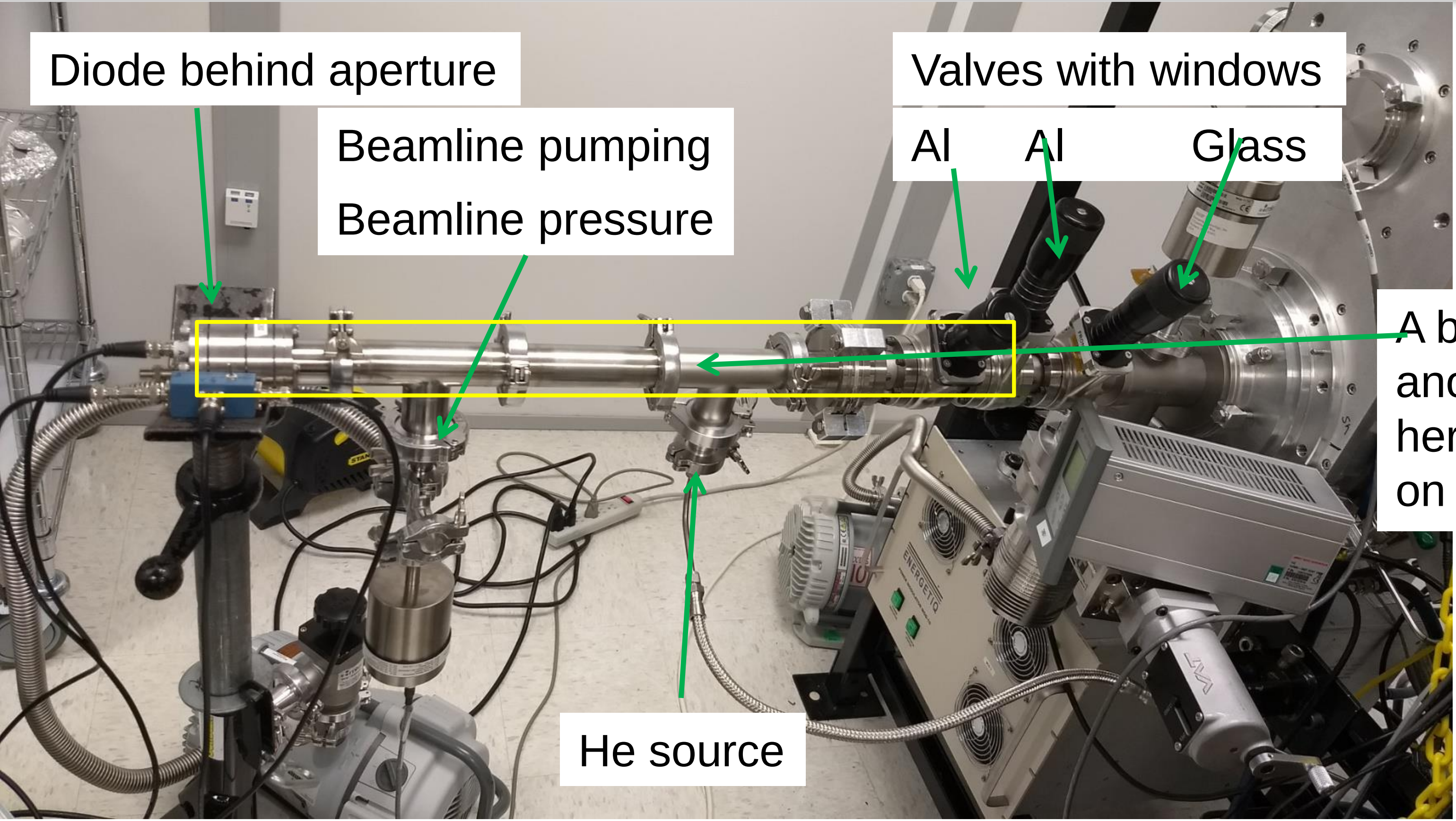
He is completely transparent.

That's OK. If our signal varies with He line density, it's not in that wavelength region.

Diode reponse (AXUV-100) is quite flat over the region of interest….



EQ-10



Diode behind aperture
Beamline pumping
Beamline pressure
Valves with windows
Al
Al
Glass
He source
A bit of black-anodized foil liner here to cut down on reflections

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Process --

- Ignite plasma in Argon; switch to Neon…(Neon ionization potential a bit too high?)
- Establish operating condition
- Evacuate beamline
- Measure power with 2-foil method (calibrates foil transmission)
- With one foil in, vary beamline He pressure
- Note diode signal, pressure

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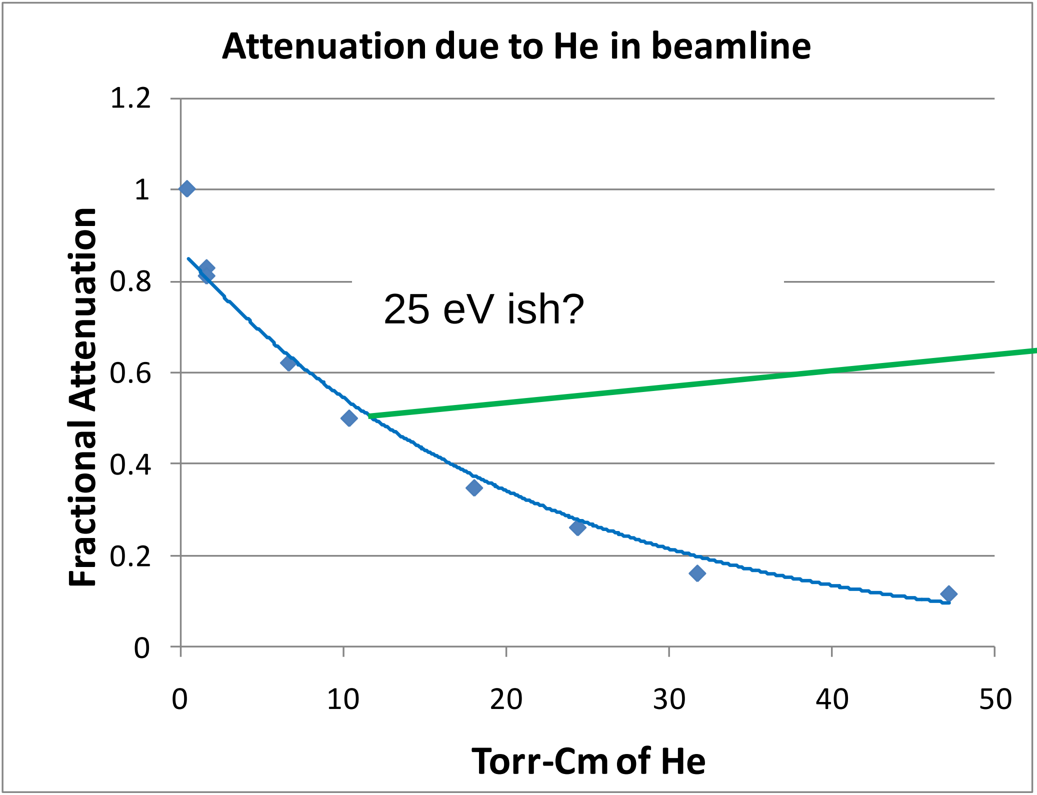
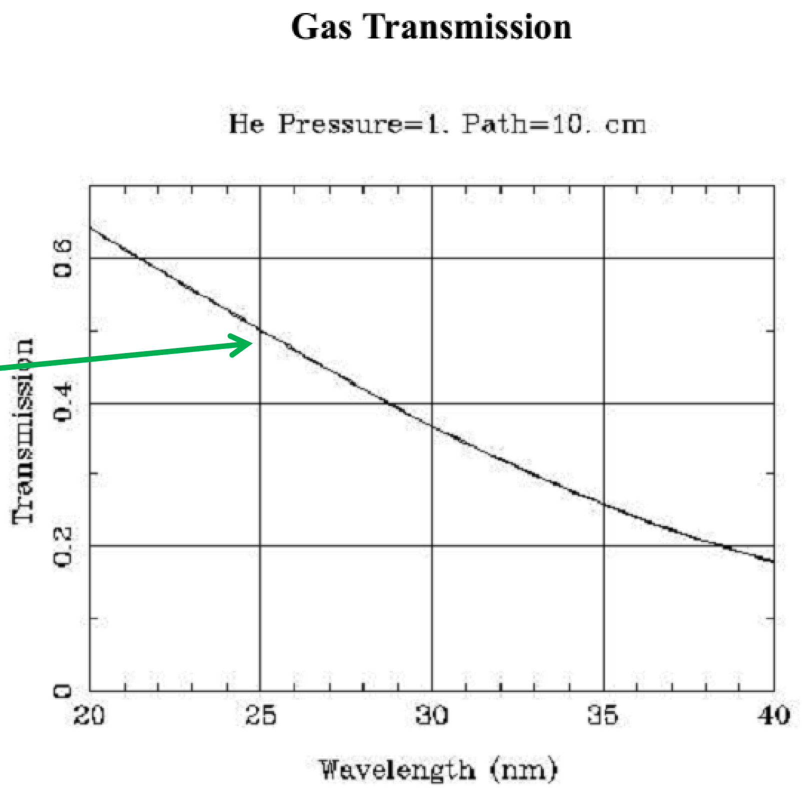
Operating point; various constraints -

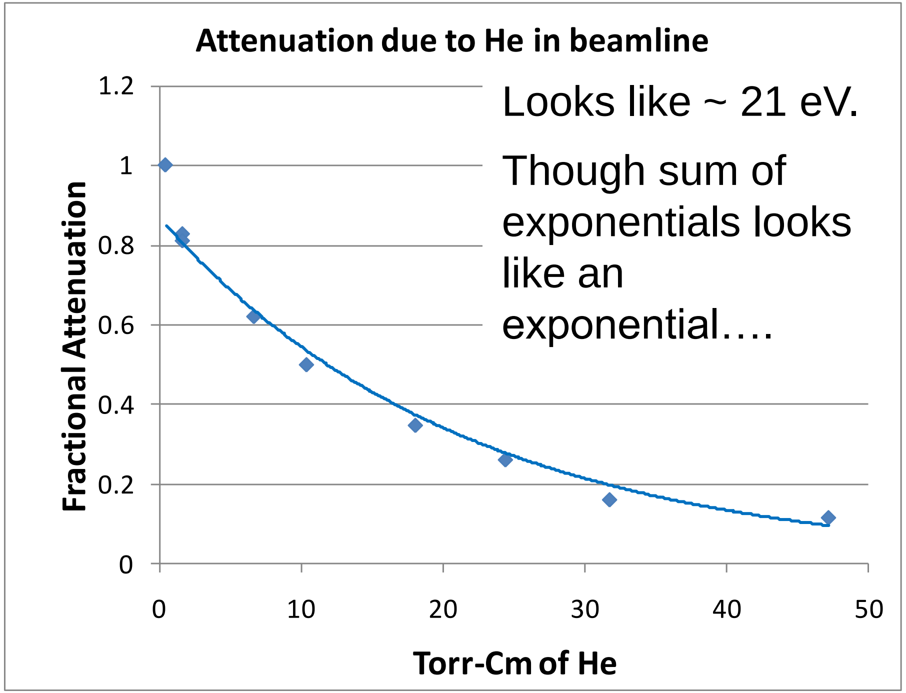
- Choose a conservative operating point -- about 1.4 J/pulse, 2000 Hz… about 4 kW DC power into pulse shaping system…
- Discover – can't operate at 600 mT pressure. Wrong MFC in the system… max pressure available ~ 170 mT.
  - Could fix this – but it's Tuesday night and my flight is Thursday…. And it's supposed to be a theory presentation anyway…
- Move on. Make the power measurement. Get ~ 19 W with double-foil method.
- Now vary helium pressure in the beamline, note signal decay…

Match measurement against CXRO calculation



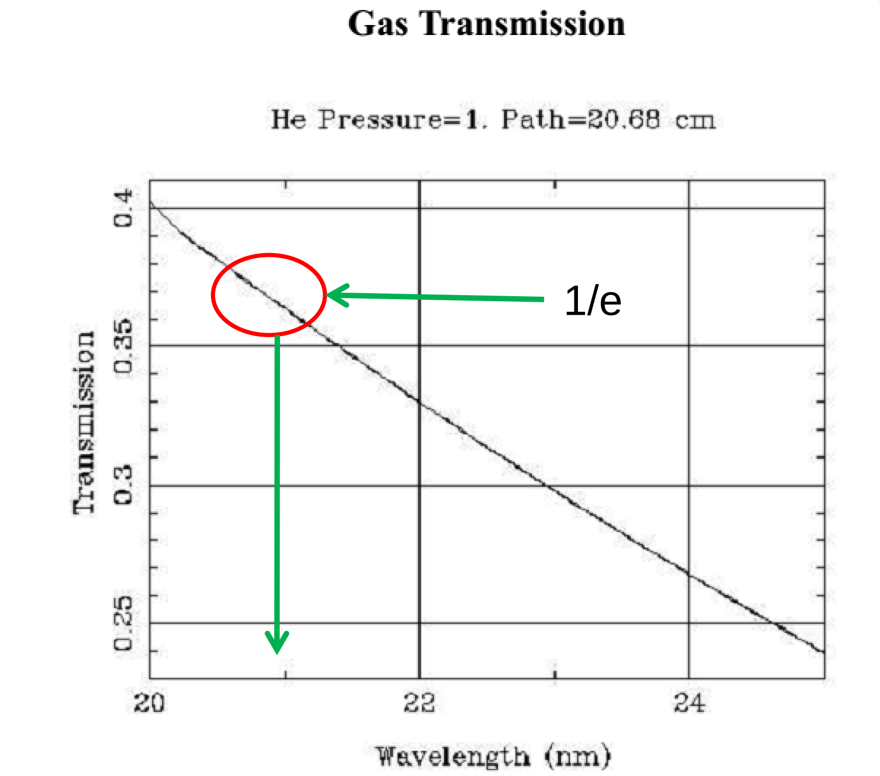


More carefully.. Fit the exponential – get 1/e of 20.68 torr-cm, → 21 eV radiation



Looks like ~ 21 eV.

Though sum of exponentials looks like an exponential….



We have way too much energy/particle to get Ne IV… what's a more likely charge state?

Plasma	Xe +10 (XI)	Ne +3 (IV)	Ne +3 (IV)	Ne +6 (VII)	Ne +7 (VIII)	Ne+8 (IX)
pressure, mt	100	600	172	172	172	172
ev/pulse/particle	8753.7	1459.0	5089.4	5089.4	5089.4	5089.4
Sum of ionizations	806	126	126	507	714	953
Ratio	10.86	11.58	40.39	10.04	7.13	5.34
	Xenon Reference state	*Tried for this. Couldn't raise density enough.*	*This state probably can't exist -- burned through.*	*These two states most likely.*	*Both have lines consistent with measurements*	*Helium-like Ne -- can't burn past this state - ionization barrier.*

Calculate with all states; get these ionization fractions..

Ne IV (3.2e-08)

Ne V (3.5e-05)

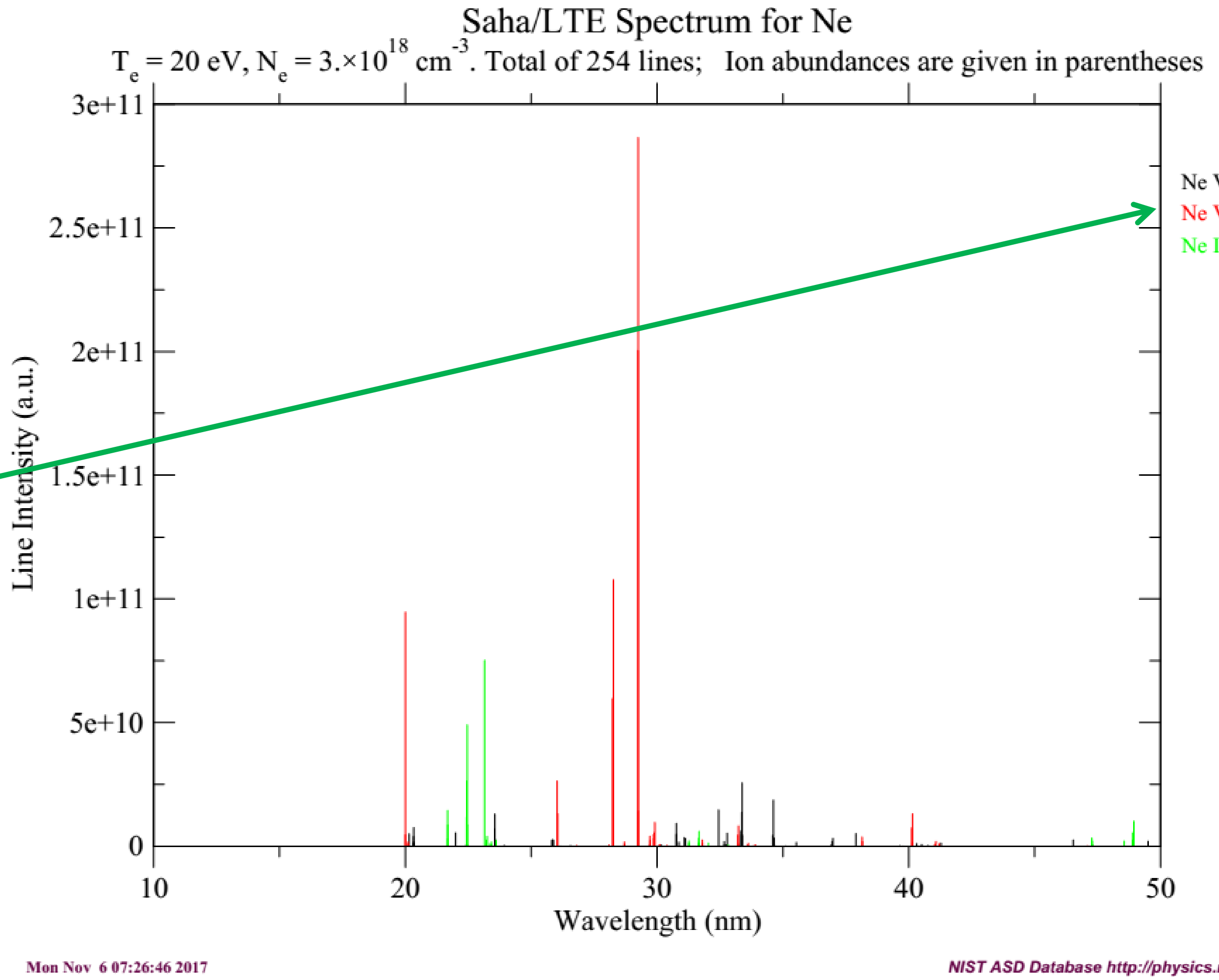
Ne VI (7.2e-03)

Ne VII (2.1e-01)

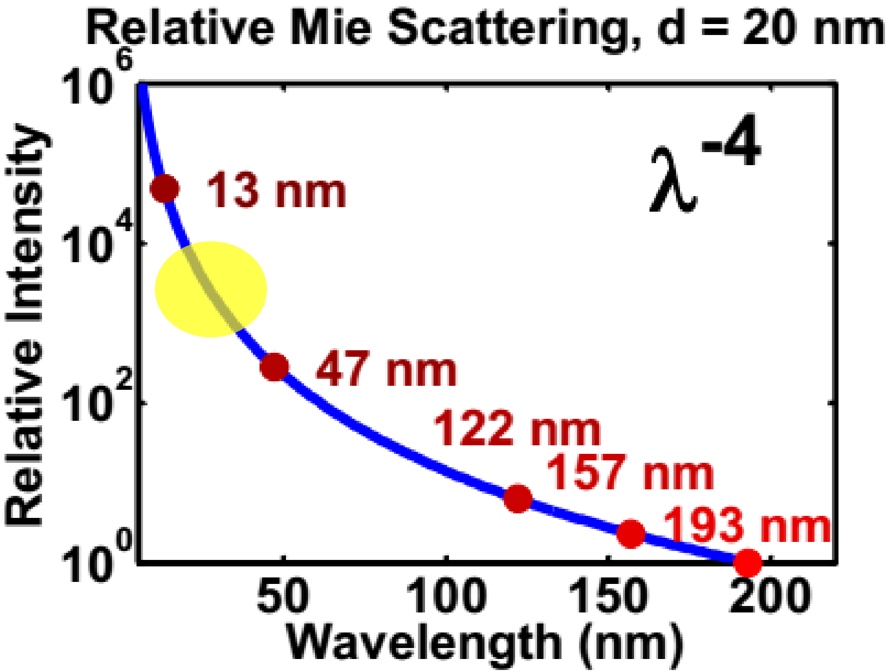
Ne VIII (6.3e-01)

Ne IX (1.5e-01)

Measurement is not inconsistent with a NIST spectral calculation, using all lines and three most likely charge states.



Conclusions - Is this useful for metrology?



Theoretically, we should be able to produce significant power between 20 and 50 nm.

In a very crude and un-optimized experiment, we estimate 19 W/2PI in this range, with 4 kW input power (could go to 7 kW)

If we can increase pressure and avoid wasting energy on high charge states, 100 W should be possible.

Ongoing…

- Replace the MFC, get to higher pressures.
- Need more information on preferred wavelengths – multiple lines? Broadband?
  - (is there a market??)
- Is wavelength selection necessary? Do multilayer mirrors exist that might works?
- Where can we find an appropriate spectrometer?
- I also took data with an Argon plasma. Actually saw more power than with Neon – but NIST is missing most of the rate coefficients, so couldn't connect theory→ experiment. Need a spectrometer to proceed.

Thank you for your attention!